High Performance Concrete Bridges

ALABAMA • COLORADO

NEBRASKA • NEW HAMPSHIRE

NORTH CAROLINA • OHIO • TEXAS

VIRGINIA • WASHINGTON

U.S. Department of Transportation
Federal Highway Administration

Route 104 Bridge Over the Newfound River, Bristol

General Description The HPC bridge is of simple-span construction, nominally 20 m (65 ft) long. The bridge consists of two through-traffic lanes, a shoulder, a left-turn lane, and a sidewalk. The width of the deck is 18 m (57 ft-6 in) and the thickness of the deck is 229 mm (9 in). Load-carrying elements consist of five Type III American Association of State Highway and Transportation Officials (AASHTO) prestressed concrete I-girders. The Route 104 HPC bridge was completed in 1996.

Outline of HPC Features Concrete mixes for the bridge elements were varied according to the demands of the particular application. Concrete strength, durability properties, and other characteristics were selected for the bridge elements and were specified in the project documents. The design strengths were:

Element	Compressive Strength
Beams @ Transfer	45 MPa (6500 psi)
Beams @ 28 days	55 MPa (8000 psi)
Deck @ 28 days	41 MPa (6000 psi)

All mixes included a set retarder and high-range water-reducing admixture. Silica fume was used as the mineral admixture. Temperature-match curing was used to evaluate beam (cylinder) concrete strength before transfer of prestressing for the beams.

Preliminary Deck HPC Evaluation Three bridge deck concrete mixes were selected from laboratory tests for field trials. For each mix, two slabs 4.9 m (16 ft) long by 1.2 m (4 ft) wide by 2.4 m (8 ft) thick were constructed, one with epoxy-coated reinforcement and one with uncoated reinforcement. These slabs were exposed to truck traffic over the winter of 1995/1996 at a Waste Management, Inc. site. After a winter's exposure, the slabs were qualitatively checked for cracking and the condition of the reinforcement using core samples. Research conducted by the University of New Hampshire found that one of the three concrete mixtures attained superior durability performance with respect to freeze-thaw durability, scaling resistance, abrasion resistance, and moment capacity. No significant differences were found between the structural performance of epoxy-coated and uncoated reinforcements. The capacities of the slabs were tested in the laboratory after exposure to truck traffic. All slabs exhibited excellent ductility, even after the exposure to truck traffic, attaining more than 50.8 mm (2 in) of mid-span deflection before failure for simple spans of 3.2 m (10 ft-6 in). All slabs also exhibited excellent strength, exceeding the design strengths by more than 30 percent in all cases.

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Concrete with enhanced durability and strength characteristics. Under the Strategic Highway Research Program (SHRP), more than 40 concrete and structural products were developed. To implement the new technology of using High-Performance Concrete (HPC), the Federal Highway Administration (FHWA) has a program underway to showcase bridges constructed with HPC. The objective is to advance the use of HPC to achieve economy of construction and long-term performance.

Concrete Evaluation The following concrete properties were measured in the preliminary deck HPC evaluation and in the HPC bridge:

- Slump
- Scaling
- Air Content
- Rapid Chloride Permeability
- Water Content
- Strength
- Chloride Intrusion
- Freeze-Thaw Durability
- Abrasion Resistance

Deflection of the slabs in the preliminary HPC deck evaluation and in the HPC bridge under dead and live loads was measured to determine creep and shrinkage effects and stiffness under the applied loads. Temperature and strain measurements continue to be recorded hourly and downloaded weekly.

Construction The HPC bridge contract was awarded in 1995. The bridge was constructed in 1996 and evaluation of the structure is ongoing. Weaver Brothers Construction Company, Inc. (Concord, NH) was the prime contractor, and Beck and Belucci, Inc. (Franklin, NH) was the bridge subcontractor. Unistress, Inc. of Pittsfield, MA was the beam fabricator. The ready-mix concrete supplier was Persons Concrete, Inc. of Winnisquam, NH (Campton, NH plant). Cotton mats used in the deck curing process (similar to what is done in Texas), led to good results, with no cracks in the bridge deck observed for the first year.

Benefits The bridge is performing well. The exposed concrete deck surface is virtually crack-free and has shown no scaling or freeze-thaw damage after four winters. Excellent long-term durability and structural performance is expected.

In 1999, the New Hampshire Department of Transportation constructed a second HPC bridge. This second bridge is located upstream from the first and carries traffic on Route 3A over the Newfound River.

U.S. Department of Transportation
Federal Highway Administration

Updated August 2000
FHWA-RD-00-119

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Route 3A Bridge Over the Newfound River, Bristol

General Description The HPC bridge is a simple-span structure, 18.3 m (60 ft) long. The bridge consists of two travel lanes, shoulders, and one sidewalk. The bridge superstructure is 12.0 m (39.5 ft) wide and consists of four New England Bulb-Tee (NEBT) prestressed concrete girders spaced 3.5 m (11.5 ft) on center, with a 229-mm- (9-in-) thick deck. The NEBT girder section, which was recently developed for the region as a new economical section, incorporates the use of HPC and 15-mm- (0.6-in-) diameter low-relaxation prestressing strands. The bridge deck consists of 89-mm- (3.5-in-) thick precast prestressed deck panels overlaid with 140 mm (5.5 in) of cast-in-place HPC concrete. Conventional concrete, 28 MPa (4000 psi), was used in the at-grade approach slabs for comparison purposes.

Outline of HPC Features Concrete mixes for the bridge elements were varied according to the demands of the particular application. Concrete strength, durability properties, and other characteristics were selected for the bridge elements and were specified in the project documents. The design strength requirements were:

Element	Compressive Strength
Beams @ Transfer	38 MPa (5500 psi)
Beams @ 28 days	55 MPa (8000 psi)
Deck @ 28 days	41 MPa (6000 psi)

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Actual average beam strengths exceeded 45 MPa (6500 psi) at transfer and 72 MPa (10,400 psi) at 28 days. Average deck strength exceeded 58 MPa (8400 psi) at 28 days.

The permeability requirements were:

Element	Permeability
Beams @ 56 days	Less than 1500 coulombs
Deck @ 56 days	Less than 1500 coulombs

Actual values were less than 600 coulombs for the beam concrete and less than 1300 coulombs for the deck concrete.

Concrete Evaluation The following concrete properties were measured in the HPC bridge:

- Slump.
- Air Content.
- Rapid Chloride Permeability.
- Water Content.
- Strength.
- Chloride Intrusion.
- Freeze-Thaw Durability.

In addition, evaluations of the performance of precast, prestressed, stay-in-place deck slabs, and concrete strains in the composite slab system and in the NEBT beams under load testing and service conditions are ongoing.

Instrumentation Two of the girders were instrumented with vibrating wire strain gauges located within the bottom flanges, and thermistors (temperature measurement devices) located throughout the girder depth. Girder strain measurements were taken at the release of the prestressing strands, prior to transportation to the site, after erection, and periodically after deck placement. Thermistors were also placed in the deck to measure temperature differentials within the concrete and to correlate ambient freeze-thaw cycles with those within the deck concrete.

Construction The general contractor of the bridge was R.S. Audley of Bow, NH, and the prestressed concrete beam and subdeck panel fabricator was Northeast Concrete Products of Plainville, MA. The ready-mix supplier was Persons Concrete, Inc. of Winnisquam, NH (Campton, NH plant). The HPC bridge construction began in October 1998. The girders were cast in April 1999 and the deck was completed in June 1999. The bridge was opened to traffic on June 25, 1999.

Benefits Greater durability with reduced long-term maintenance will be derived by using HPC in the girders. Also, by using HPC in the recently developed New England Bulb-Tee girders, the designers were able to achieve wider girder spacings and to use a shallower girder than if conventional concrete had been used. Experience from the first HPC bridge, the Route 104 Bridge over the Newfound River, showed that some difficulties were encountered with placing a fully cast-in-place deck across the long girder spacings. Therefore, the Route 3A bridge employed precast prestressed concrete deck panels as stay-in-place deck formwork that then became composite with the cast-in-place deck. The use of the subdeck panels aided the contractor immensely during construction. ■

U.S. Department of Transportation
Federal Highway Administration

Updated August 2000
FHWA-RD-00-120

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120th Street and Giles Road Bridge, Sarpy County

General Description This HPC bridge was built within 1 km (0.62 mi) of a very similar newly completed bridge of standard construction. The bridge consists of three equal 22.9-m (75-ft) spans and is 25.8 m (84.7 ft) wide. The HPC bridge used seven NU1100 (1100-mm-high) simple-span girders made continuous for live load using negative-moment reinforcement in the deck. The NU girder series is metric. These Bulb-Tee girders were developed in a girder optimization program conducted by the University of Nebraska at Omaha. Girder spacing is 3.8 m (12.4 ft) on center and the deck thickness is 191 mm (7.5 in). Sarpy County in Nebraska conducted the project, in cooperation with the Nebraska Department of Roads (NDOR) and the University of Nebraska.

Outline of HPC Features The HPC components had both compressive strength requirements and chloride permeability requirements, depending on the application in the structure. The strength requirements for the HPC elements were:

Element	Compressive Strength
Girders @ Transfer	38 MPa (5500 psi)
Girders @ 56 days	83 MPa (12,000 psi)
Deck @ 56 days	55 MPa (8000 psi)

A chloride permeability requirement of less than 1800 coulombs at 56 days was specified for the deck. The water-to-cementitious material ratio for the girders was specified as less than 0.28. The cementitious material included portland cement, fly ash, and silica fume.

Pretensioned Girders The girders were pretensioned with thirty or thirty-four (depending on the span) 12.7-mm- (0.5-in-) diameter strands at 50-mm (2-in) center-to-center spacing. Either 10 or 12 strands were debonded near the ends of the girders. The beams were steam-cured, but the steam temperature and the concrete temperature at the centroid of the bottom flange were not allowed to exceed 71°C (160°F).

Substructure The interior bents and the abutments were constructed using concrete with $f'_c = 21$ MPa (3000 psi).

Deck Silica fume was used in the deck concrete to meet the chloride permeability requirement of less than 1800 coulombs at 56 days. The deck concrete after finishing was kept damp by nozzles creating a mist such that the water did not flow or accumulate on the surface for at least 5 h. Afterwards, wet-mat curing was used for 8 days. Air content was between 5 percent and 7.5 percent, and permeability was less than 1800 coulombs at 56 days.

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Concrete Tests The following properties were measured for both the girder and the deck concrete:

- Compressive Strength.
- Chloride Permeability.
- Flexural Strength.
- Modulus of Elasticity.
- Splitting Tensile Strength.
- Shrinkage.
- Abrasion Resistance.

Instrumentation The girders were instrumented to provide data on behavior from placement of concrete through long-term performance under dead and live load in the completed bridge. Instrumentation included embedded thermocouples, electrical resistance strain gauges, and vibrating wire gauges. Measurements at the surface were made using external mechanical gauges. Girder camber, end rotation, prestressing force, and shrinkage were also measured. The deck had clusters of gauges at 12 locations. These gauges included vibrating wire gauges, electrical resistance strain gauges, and thermocouples. Diaphragms had points mounted on the surface to measure strain using mechanical gauges.

Construction The bridge contract was let in April 1995. The general contractor was Hawkins Construction Company. The girders were produced in Fall 1995, and the deck was cast in Spring 1996. Wilson Concrete Company was the beam fabricator and Ready Mixed Concrete Company of Omaha was the ready-mix concrete supplier. The bridge was opened to traffic in 1996.

A visit to the bridge in May 2000 found some transverse cracks along the bottom of the deck, but these cracks were similar to those observed on decks constructed with traditional concrete. The cracks were not evident along the top of the deck. The conclusion of the visit was that the deck was performing well.

Benefits The benefits are apparent as fewer girders were required in the HPC superstructure. The nearby bridge constructed without HPC provides a direct comparison of the durability aspects of HPC.

U.S. Department of Transportation
Federal Highway Administration

Updated August 2000
FHWA-RD-00-121

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Alabama Highway 199 Over Uphapee Creek, Macon County

General Description The main bridge at Uphapee Creek is a replacement for a bridge that has suffered from streambed scour resulting from sand and gravel mining downstream. The route carries heavily loaded sand and gravel trucks and logging trucks. On the same project, within 1.6 km (1 mi) of this structure, a flood-relief bridge and a bridge over Bulger Creek are being replaced that will not utilize HPC. The HPC project at Uphapee Creek consists of seven 34.7-m (114-ft) AASHTO Bulb-Tee (BT) prestressed concrete girder spans. All spans are simple-span construction on either drilled-shaft or driven-steel-pile foundations. Girders are spaced at 2.67 m (8.75 ft), giving a 12.2-m (40-ft) roadway. The deck thickness is 178 mm (7 in). The Alabama Department of Transportation conducted the project in cooperation with Auburn University.

Outline of HPC Features The HPC project specifications required high 28-day compressive strength, high early-strength, and low permeability. Specified compressive strengths for the HPC elements were:

Element	Compressive Strength
Girders@Transfer	55 MPa (8000 psi)
Girders@28 Days	69 MPa (10,000 psi)
Deck@28 Days	41 MPa (6000 psi)
Cap and Columns @28 Days	41 MPa (6000 psi)

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Pretensioned Girders The AASHTO BT-54 girders are 1372 mm (54 in) deep and are pretensioned with forty-two 15.2-mm- (0.6-in-) diameter, low-relaxation, 1862-MPa (270-ksi) strand. Strands are draped to reduce stresses at the ends. The girders were steam-cured to obtain high early-release strength.

Substructure Intermediate bents and the end abutments were constructed using concrete with f'c= 41 MPa (6000 psi). The design was based on a compressive strength of 21 MPa (3000 psi).

Deck The 28-day compressive strength of the deck concrete was 41 MPa (6000 psi). The design was based on 28 MPa (4000 psi). Special curing of the deck concrete required that it be kept moist by fogging until wet curing was begun. Specified entrained air content was between 3 percent and 5 percent.

Concrete Tests The following properties were measured for both the girder and deck concretes:
- Compressive Strength
- Chloride Permeability
- Flexural Strength
- Abrasion Resistance
- Modules of Elasticity
- Creep and Shrinkage
- Splitting Tensile Strength

Instrumentation The girders were instrumented to monitor behavior from placement of concrete through long-term service life under dead, live, and impact loading. Instrumentation consists of embedded thermocouples to monitor and record temperature gradient across the girder depth, and electrical resistance strain gauges and vibrating wire strain gauges to measure and record strains throughout the girder length and depth. Calibrated live-load tests will be performed in August 2000. External gauges will be utilized to measure and record deflections.

Construction The project was let to contract in March 1998, and Clark Construction Company, Inc. was the contractor. The girders were fabricated in fall 1998 by Sherman Prestressed Concrete. The substructure was constructed during summer 1999. The ready-mix concrete supplier was Blue Circle Williams. The bridge was opened to traffic in April 2000.

Benefits By using HPC in the girders, the bridge design was changed from a 243.8-m (800-ft) bridge made up of eight 30.5-m (100-ft) spans to a bridge made up of seven 34.7-m (114-ft) spans using one fewer girders. The savings is the cost of one pier and the requirement to cast thirty-five 34.7-m (114-ft) girders instead of forty-eight 30.5-m (100-ft) girders.

U.S. Department of Transportation
Federal Highway Administration

Updated July 2000
FHWA-RD-00-114

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Interstate 25 Over Yale Avenue, Denver

General Description The completed HPC bridge replaced a four-span cast-in-place T-girder bridge. The HPC bridge solution was to construct a two-span structure using box beams made continuous over the center support. The two spans are 34.5 m (113.3 ft) and 30 m (98.6 ft) long, respectively. The 42-m- (138-ft-) wide bridge was built in phases to permit traffic flow (151,000 average daily traffic) in both directions during construction. The new bridge improved clearances over Yale Avenue without a significant change in the grade of I-25. The Colorado Department of Transportation (CDOT) conducted the project in cooperation with the University of Colorado at Boulder.

Outline of HPC Features The HPC elements and compressive-strength requirements will be:

Element	Compressive Strength
Girders @ Transfer	45 MPa (6500 psi)
Girders @ 56 Days	69 MPa (10,000 psi)
Deck & Substructure @ 28 Days	34 MPa (5000 psi)

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Pretensioned Beams The pretensioned concrete box beams are 1700 mm (67 in) wide and 750 mm (30 in) deep. The beams utilized 15.2-mm- (0.6-in-) diameter strands at 51-mm (2-in) center-to-center spacing. The University of Colorado performed testing utilizing strand pull-out strength, transfer length, and development length. The results are documented in Report No. CDOT-DTD-R-98-7, Colorado Study on Transfer and Development Length of Prestressing Strand in High-Performance Concrete Box Girders, by Cooke, Shing, and Frangopol.

Substructure The piers, columns, and abutments were constructed with the deck concrete mix. This resulted in some reduction of member sizes and increased durability of low-level elements exposed to spray and splash from Yale Avenue traffic.

Deck The CDOT deck concrete specification at the time of the initiation of the project called for a 28-day strength of 31 MPa (4500 psi), with mix approval based on a 28-day strength of 39 MPa (5625 psi). In comparison, the deck and substructure concrete for this bridge required a 28-day strength of 40 MPa (5800 psi) for mix approval. The actual deck strength after 90 days averaged 41.8 MPa (6061 psi) and the air content averaged 5.5 percent. No fly ash or silica fume was added to the mix.

Concrete Tests In addition to the tests indicated by the properties in the proceeding table, the following concrete properties were measured to establish a database:

Deck*	Girders*
• Air Content	• Air Content
• 56- & 90-Day Compressive Strength	• 90-Day Compressive Strength
• Creep	• Creep
• Shrinkage	• Shrinkage
• Modulus of Elasticity	• Modulus of Elasticity
• Rapid Chloride Permeability	• Splitting Tensile Strength
• Freeze-Thaw	• Modulus of Rupture

*Except for air content, these characteristics were used in confirmation of design assumptions and were not part of the project acceptance criteria for HPC.

Instrumentation The completed bridge was instrumented to measure temperature and strain variations. This was combined with deformation measurements to determine how the bridge behaves in response to creep, shrinkage, temperature changes, dead load, and live load. The first girder camber measurements occurred at prestress transfer and then at each stage of girder loading until the bridge was completed.

Construction The wind and low humidity in Colorado are a problem and can contribute to deck cracking. A membrane-forming curing compound was placed immediately upon finishing and a moist cure was started when the deck concrete could be walked on without damage. The moist cure was continued for 5 days.

Construction on this project began in November 1996 and was completed in June 1998.

Benefits The initial cost benefits are the elimination of two column/pier lines. It is expected that the more durable concrete will provide increased resistance to traffic wear, environmental factors, and the effects of deicing chemicals. ■

U.S. Department of Transportation
Federal Highway Administration

Updated August 2000
FHWA-RD-00-115

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State Route 22 at Milepost 6.57, Guernsey County

General Description The High-Performance Concrete (HPC) structure is a single-span, prestressed concrete box-beam bridge composed of 12 side-by-side 1219-mm- (48-in-) wide by 1067-mm- (42-in-) deep beams topped with a non-composite asphalt wearing surface. The bridge is 14.6 m (48 ft) wide, with a single span measuring 35.2 m (115 ft-6 in) bearing to bearing. The abutments are stub-type on a single row of H-section steel piles. Construction was phased to eliminate a detour during the replacement of the existing 21-m (70-ft) single-span steel beam and concrete deck structure. The Ohio Department of Transportation (ODOT) conducted the project in cooperation with the University of Cincinnati.

Outline of HPC Features HPC was used in both the beams and the stub abutments. The prestressed concrete beams were designed based on a 41-MPa (6000-psi) release strength and a 69-MPa (10,000-psi) ultimate strength at 56 days. The box beams incorporated 15.2-mm (0.6-in) strands to achieve the most efficient use of HPC's higher strengths. The cast-in-place abutment concrete met a 55-MPa (8000-psi) design strength in 28 days. All concrete was required to have a rapid chloride permeability value of below 1000 at 56 days. Both concrete mixes incorporated the use of silica fume to obtain the required strength and durability requirements. The box beams also included a new shear-key location based on research sponsored by ODOT.

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Box-Beam Mix	per m^3	per yd^3
Cement	501 kg	846 lb
Sand	549 kg	927 lb
Gravel #8	1051 kg	1773 lb
Micro-Silica	59 kg	100 lb
Water	155 kg	262 lb
Superplasticizer	8320 mL	215 oz
Air-Entraining Agent	810 mL	21 oz
Retarder	1080 mL	28 oz

Pretensioned Beams The prestressed concrete box beams were made using 15.2-mm (0.6-in) strands at 51-mm (2-in) center-to-center spacing. The box beams are 1219 mm (48 in) wide and 1067 mm (42 in) deep.

Instrumentation The box-beam concrete was tested for compressive strength, chloride permeability, tensile strength, creep, and shrinkage. The average compressive strength for the girders was about 75 MPa (11 ksi), the modulus of rupture was approximately 8.3 MPa (1200 psi), and the rapid chloride permeability was less than 500 coulombs. Shrinkage was about 1000 microstrain and the creep coefficient was 2.1 at 1 year.

The beams for the bridge were instrumented to allow evaluation of prestressing forces, development length, heat of hydration, shrinkage, prestress losses, and flexural strength. Additional evaluation was performed during erection, temporary phased construction, truck load testing, and actual traffic testing. Data from the actual bridge members were compared to baseline values established from testing two full-size prestressed research beams. Results indicated that the cracking loads of the research beams were higher than that predicted by the American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Highway Bridges, but that the difference was attributable to the higher modulus of rupture of HPC. The research beams were loaded to 10 percent greater than the ultimate load predicted by the AASHTO Standard Specifications and they did not fail. Prestress losses were determined to be approximately 18 percent, consistent with the value calculated from the AASHTO Standard Specifications. Live load tests of the actual bridge showed that the live load distribution was in reasonable agreement with that given by the AASHTO Standard Specifications. The live load deflections were very low (less than L/2000) and the traffic-induced vibrations were not excessive.

Construction The project's letting date was July 1997. The box beams for the bridge were constructed by Prestress Services of Melbourne (KY), who worked with the University of Cincinnati to develop the HPC research beams. Ohio/West Virginia Excavating was the general contractor and the ready-mixed HPC (for the abutments) was supplied by Caldwell Concrete. The project was completed in November 1998. The bridge is open to traffic and functioning well. The University of Cincinnati published a paper on revised beam testing techniques as a result. A High-Performance Concrete Bridge Showcase was held February 23-24, 1999 in Cincinnati, OH.

Benefits ODOT's normal replacement alternatives for this bridge site would be a three-span normal-concrete slab bridge, a single-span steel or prestressed normal-concrete I-beam with cast-in-place concrete deck, or a three-span noncomposite prestressed normal-concrete box-beam bridge. The lowest cost would be the box beam, which was the original bridge type selected. Using HPC concrete and 15.2-mm (0.6-in) strands, the box beam's span range increased to offer ODOT a lowest cost single-span alternative by eliminating two substructure units that would be required for the current low-cost structure. In addition, the structure's life will be enhanced because of the durability benefits associated with HPC's low permeability. ■

U.S. Department of Transportation
Federal Highway Administration

Updated August 2000
FHWA-RD-00-118

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San Angelo Bridge, U.S. Route 67, San Angelo

General Description The San Angelo Bridge, more formally known as the North Concho River, U.S. 87, and South Orient Railroad Overpass, consists of eastbound and westbound U.S. Route 67 main-lane bridges. The eastbound main-lane bridge is HPC. The westbound main lanes use conventional concrete mixes, except for a high-performance/normal-strength concrete deck in five of the nine spans. The geometry of the crossing is such that the eastbound HPC beam spans vary from 19.4 m (63.8 ft) to 47.9 m (157 ft). The simple-span AASHTO Type IV prestressed concrete I-beams are used in seven spans, and Texas Type B prestressed concrete I-beams are used in the short eighth span. The Texas Department of Transportation (TxDOT) conducted the project in cooperation with the University of Texas at Austin.

Outline of HPC Features The concrete strength of the bridge beams varied from 40 MPa (5800 psi) to 102 MPa (14,800 psi) according to the demand of the particular application. The design strengths were specified at 28 days for the deck and piers. The design strength for the beams was specified at 56 days to account for the strength gain with time that is typical of many higher strength concretes. The strengths of the eastbound bridge were:

Element	Compressive Strength
Beams@Transfer	61-74 MPa (8900-10,800 psi)
Beams@56 Days	40-101 MPa (5800-14,700 psi)
Piers	41 MPa (6000 psi)
Pier Cap	55 MPa (8000 psi)
Deck	41 MPa (6000 psi)
Prestressed Concrete Subdeck Panels	41 MPa (6000 psi)

To facilitate placement of the concrete in the I-beams, set retarder and high-range water-reducing admixtures were used. Accelerated curing was not used. Cement was partially replaced with fly ash in all mixes.

Prestressed Beams The AASHTO Type IV prestressed concrete I-beams were 1372 mm (54 in) deep and were designed with straight pretensioned strands and draped post-tensioned strands. All strands are 15.2 mm (0.6 in) in diameter. The pretensioned strands are spaced at 51 mm (2 in), and two ducts carry the draped post-tensioned strands. Transfer- and development-length tests were conducted in this project to obtain FHWA approval for use of the 15.2-mm-(0.6-in-) diameter pretensioned strands at 51-mm (2-in) spacing.

HIGH-PERFORMANCE CONCRETE

Concrete with enhanced durability and strength characteristics. Under the Strategic Highway Research Program (SHRP), more than 40 concrete and structural products were developed. To implement the new technology of using High-Performance Concrete (HPC), the Federal Highway Administration (FHWA) has a program underway to showcase bridges constructed with HPC. The objective is to advance the use of HPC to achieve economy of construction and long-term performance.

Piers The substructure consists of a cast-in-place reinforced concrete single column with tapered cap. A window in each column complements openings in the superstructure's traffic railing.

Deck The deck is composite, cast-in-place, reinforced concrete with precast, prestressed concrete subdeck panels. One task in this project was to accumulate field experience with the use of high-strength versus normal-strength high-performance concrete in cast-in-place concrete deck construction. A reinforcing bar with a new pattern of deformation was also used. This bar was developed by the University of Kansas to provide improved bond characteristics, and it replaced the standard reinforcement in the cast-in-place concrete decks of two spans.

Construction Construction of this bridge began in June 1995. The contractors were Jascon, Inc., Uvalde, Texas, and Reece Albert, Inc., San Angelo, Texas. The cast-in-place concrete was provided by Concho Concrete Company, San Angelo, Texas. The prestressed concrete I-beams were fabricated by Texas Concrete Company, Victoria, Texas, while the prestressed concrete subdeck panels were fabricated by Bexar Concrete Works, San Antonio, Texas. The project was completed and opened to traffic in January 1998.

Long-Term Performance TxDOT, in cooperation with the University of Texas at Austin, has a long-term monitoring project underway to continue reading the extensive instrumentation installed in the bridge, as well as to make visual observations and comparisons between the HPC elements and normal concrete elements. The interpretation of the results from the extended data acquisition will document actual performance and should lead to improved design guides for HPC use and better construction specifications.

Benefits The use of the high-strength characteristic of high-performance concrete in the beam design allowed a significant reduction in the number of beams and the reduction of one span. It is anticipated that the improved durability will result in reduced long-term maintenance costs and longer service life.

U.S. Department of Transportation
Federal Highway Administration

Updated August 2000
FHWA-RD-00-117

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Louetta Road Overpass, State Highway 249, Houston

General Description Texas State Highway 249 was upgraded from a four-lane, at-grade road to a limited-access freeway. Consequently, two overpass structures have been built at Louetta Road to carry three lanes in each direction, plus shoulders and ramp transitions. The bridges are three spans each, nominally 40 m (130 ft) per span. Beams are pretensioned and are U-shaped. At the interior bents, each beam is supported by a single post-tensioned pier. All beams and piers were designed and fabricated using high-performance/high-strength concrete. The composite decks are precast concrete subdeck panels with cast-in-place concrete topping. For comparison purposes, the southbound main-lane bridge has a high-performance/high-strength cast-in-place concrete deck, whereas the northbound main-lane bridge has a high-performance/normal-strength cast-in-place concrete deck. The Texas Department of Transportation (TxDOT) conducted the project in cooperation with the University of Texas at Austin.

Outline of HPC Features The concrete strength of the bridge elements varies according to the demand of the particular application. The design strengths were specified at 28 days for the deck and piers. The design strength for the beams was specified at 56 days to account for the strength gain with time that is typical of many higher strength concretes. Strengths were:

Element	Compressive Strength
U-Beams @ Transfer	48-61 MPa (6900-8800 psi)
U-Beams @ 56 Days	69-90 MPa (10,000-13,000 psi)
Piers	69 MPa (10,000 psi)
Deck (Southbound)	55 MPa (8000 psi)
Deck (Northbound)	28 MPa (4000 psi)
Prestressed Concrete Subdeck Panels	55 MPa (8000 psi)

Due to the large number of closely spaced prestressing strands, placement of the concrete in the U-shaped beams required superior workability and the use of a set retarder and high-range water-reducing admixture. No accelerated curing was used. Cement was partially replaced with fly ash in all mixes.

Pretensioned Beams The pretensioned beams were fabricated using a newly developed cross-section. The TxDOT U54 beams are trapezoidal in cross-section, but open at the top with flanged stems. The width of the beam across the top of the stems is 2.4 m (8 ft); the beams are 1372 mm (54 in) deep. The beam stems are 126 mm (5 in) thick and the thickness of the bottom flange can accommodate three rows of strands. Except for the interior beams of the shortest span where a 12.7-mm- (0.5-in-) diameter strand was used, 15.2-mm- (0.6-in-) diameter strand spacing at 50

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mm (2 in) on center was used for pretensioning. Transfer- and development-length tests were conducted in this project to obtain FHWA approval for the use of 15.2-mm- (0.6-in-) diameter pretensioned strands at 50-mm (2-in) spacing.

Piers The piers are hollow 991-mm (3.25-ft) square segments with chamfered corners. Two walls are 190.5 mm (7.5 in) thick to accommodate three 34.93-mm- (1.38-in-) diameter post-tensioning bars. The other two walls are 102 mm (4 in) thick. The use of this pier system allowed speedy construction in the field to provide beam supports and the effective utilization of high-performance concrete in the substructure.

Deck The deck is composite, cast-in-place, reinforced concrete with precast, prestressed concrete subdeck panels. One task in this project was to accumulate field experience with the use of high-strength versus normal-strength high-performance concrete in cast-in-place concrete deck construction.

Construction Construction of the Louetta Road Overpass began in February 1994. The contractor was Williams Brothers, Inc. of Houston. The U-beams were fabricated by Texas Concrete Company of Victoria, Texas. Cast-in-place concrete was provided by Lopez-Gloria Construction Services, Inc. of Houston. The bridge was opened to traffic in May 1998.

Long-Term Performance TxDOT, in cooperation with the University of Texas at Austin, has a long-term monitoring project underway to continue reading the extensive instrumentation installed in the bridge, as well as to make visual observations of the HPC elements. The interpretation of the results from the extended data acquisition will document actual performance and should lead to improved design guides for HPC use and better construction specifications.

Benefits The use of the high-strength characteristic of high-performance concrete in the beam design allowed simple-span construction for this overpass. Otherwise, a more complicated and costly superstructure and/or substructure design would have been required due to the underneath-roadway constraints. Aesthetics were considered, and the U-beams with a single pier per widely spaced beam offer an attractive alternative to typical designs. ■

U.S. Department of Transportation
Federal Highway Administration

Updated August 2000
FHWA-RD-00-116

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Route 40 Over the Falling River, Lynchburg District

General Description The bridge, located in Brookneal, VA, is a two-lane 13.4-m- (44-ft-) wide structure made up of four equal spans that are 24.4 m (80 ft) long. Each of the simple spans consists of five American Association of State Highway and Transportation Officials (AASHTO) Type IV pretensioned concrete I-beams. The beams are spaced at 3.1 m (10.3 ft) on center. The project was conducted by the Virginia Department of Transportation (VDOT) in cooperation with the Virginia Transportation Research Council.

Outline of HPC Features The HPC members had both compressive strength requirements and chloride permeability requirements based on the particular member's use in the structure.
The requirements for all elements measured at 28 days were:

Element	Compressive Strength, MPa (psi)	Chloride Permeability, coulombs
Beams@Transfer	41 (6000)	
Beams	55 (8000)	1500
Deck	28 (4000)	2500
Substructure	21 (3000)	3500

Pretensioned Beams The AASHTO Type IV prestressed concrete I-beams were pretensioned with 15.2-mm- (0.6-in-) diameter strands at 51 mm (2 in) on center. The concrete contained silica fume and had a water-to-cementitious material ratio of 0.32.

I-Beam Mix	per m³	per yd³
Type I Cement	446 kg	752 lb
Silica Fume	33 kg	55 lb
Crushed Limestone	994 kg	1675 lb
Fine Aggregate	845 kg	1425 lb
Water	151 kg	255 lb
Superplasticizer	7782 mL	202 fl oz
Retarder	934-1152 mL	24-30 fl oz
Air-Entraining Agent	124-280 mL	3.2-7.3 fl oz

Substructure Although the compressive strength of the substructure HPC was what had been typically specified for substructure concrete in Virginia, there was a permeability requirement added to the performance characteristics.

Deck The deck is 216 mm (8.5 in) thick, which is 13 mm (0.5 in) thicker than the conventional concrete deck design because of the wider beam spacing. The cementitious portion of the concrete was made with equal parts of portland cement and slag. For the actual bridge, the measured deck concrete compressive strength exceeded 55 MPa (8000 psi).

High Performance Concrete — Academia — States — Industry — FHWA — HPC

HIGH-PERFORMANCE CONCRETE

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Mix Constituent	Deck Mix, per m³ (per yd³)	Substructure Mix, per m³ (per yd³)
Type II Cement	195 kg (329 lb)	210 kg (353 lb)
Slag	195 kg (329 lb)	139 kg (235 lb)
Arch Marble	1052 kg (1773 lb)	1052 kg (1773 lb)
Natural Sand	696 kg (1173 lb)	744 kg (1254 lb)
Water	156 kg (263 lb)	154 kg (259 lb)
Superplasticizer	508-761 mL (13-20 fl oz)	0-1814 mL (0-47 fl oz)
Air-Entraining Agent	330 mL (8.6 fl oz)	113-181 mL (2.9-4.7 fl oz)
Water Reducer	2538 mL (66 fl oz)	1814-2268 mL (47-59 fl oz)

Concrete Evaluation The following properties were measured for the concrete in the beams, deck, and substructure:

Beams
- 28-day Compressive Strength
- Compressive Strength at Release
- Air Content
- Slump
- Flexural Strength
- Splitting Tensile Strength
- Modulus of Elasticity
- Permeability
- Drying Shrinkage

Deck and Substructure
- 28-day Compressive Strength
- Air Content
- Slump
- Permeability
- Temperature

Construction The contract was awarded in 1994 and construction began in early 1995. The bridge was opened to traffic in May 1996. The general contractor was W.C. English, Inc.; the precast/prestressed concrete fabricator was Ross Prestressed Concrete, Inc.; and the ready-mixed concrete supplier was Felton Brothers Transit Mix, Inc.

Benefits The HPC bridge contained five beams, compared to the seven beams needed if the bridge had been designed as a conventional concrete bridge. This resulted in a net savings of eight beams for the four-span bridge because higher strength HPC beams were used. The bid bridge construction cost was $527/m² ($49/ft²). This may be compared to the 1994 average of $624/m² ($58/ft²) for 34 bridges in the Federal-aid highway system in Virginia. The initial savings over conventional bridge concrete and construction was estimated to be 4 percent.

U.S. Department of Transportation
Federal Highway Administration

Updated August 2000
FHWA-RD-00-122

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Eastbound, State Route 18 Over State Route 516, King County

General Description The existing bridge is a two-lane structure carrying eastbound State Route 18 traffic over State Route 516. The HPC bridge is a three-span continuous structure, with a center span of 42 m (137 ft) and side spans of 24 m (80 ft). Pretensioned concrete Washington State Department of Transportation (WSDOT) W74G girders were used. The roadway deck is 11.6 m (38 ft) wide, carrying two 3.7-m (12-ft) lanes and 1.2-m (4-ft) and 3.0-m (10-ft) shoulders. The bridge is designed for earthquake zone "C" (acceleration coefficient = 0.25 g). The design used the new American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) bridge specifications. WSDOT conducted the project in cooperation with the University of Washington.

Outline of HPC Features HPC was used in the girders and in the deck. The durability and strength requirements varied according to the demands of the particular member. The contract originally specified chloride permeability requirements for the deck and girders of less than 1000 coulombs at 56 days. The contract also specified the AASHTO T277 Rapid Chloride Permeability Test as the acceptance test procedure. However, the requirement for chloride permeability was changed to a monitoring measurement for the deck rather than an acceptance criterion. The freeze-thaw durability for the girders was also measured for monitoring purposes only. The strength requirements are shown below:

Element	Compressive Strength
Girders@Transfer	51.0 MPa (7400 psi)
Girders@56 days	68.9 MPa (10,000 psi)
Deck@28 Days	27.6 MPa (4000 psi)

Pretensioned Girders The girders for the bridge used 15.2-mm (0.6-in) strands at 51-mm (2-in) center-to-center spacing. However, prior to production of the project girders, one 6.1-m (20-ft) research girder was made to test fabrication procedures and the instrumentation, and to perform some materials testing. The project girders were WSDOT W74G standard prestressed concrete I-girders that were 1880 mm (74 in) deep and were built with composite decks. No air entrainment agent was used in the girder concrete. The concrete mix proportions for the HPC girders are shown below.

Girder Mix	Per m^3	Per yd^3
Cement (Type III)	432 kg	728 lb
Fly Ash	132 kg	222 lb
Silica Fume	30 kg	50 lb
Fine Aggregate	528 kg	890 lb
Coarse Aggregate	1109 kg	1870 lb
Water	157 kg	265 lb
Water Reducer	1119 mL	29 fl oz
High-Range Water Reducer	8293 mL	215 fl oz

HIGH-PERFORMANCE CONCRETE

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Deck The deck concrete mix was the WSDOT Class 4000D concrete mix that contained fly ash and had a continuous wet cure for 14 days. This was a WSDOT-furnished mix design, but acceptance testing was performed to verify that the project criteria were satisfied. The concrete mix proportions for Washington Class 4000D concrete are shown below:

WS Class 4000D Deck	Per m^3	Per yd^3
Cement	392 kg	660 lb
Fly Ash	44 kg	75 lb
Fine Aggregate	653 kg	1100 lb
Coarse Aggregate	1009 kg	1700 lb
Water	172 kg	290 lb
Air Entrainment	6%	6%
Water Reducer Type A	Yes	Yes
Water/Cementitious Material Ratio	0.39	0.39

Concrete Evaluation The following concrete properties were measured for the project:

- Chloride Permeability
- Compressive Strength
- Coefficient of Thermal Expansion
- Creep
- Shrinkage
- Freeze-Thaw Durability
- Modulus of Elasticity
- Abrasion Resistance

The measured average values for some of these properties were:

	Girder	Deck
Compressive Strength:	74.5 MPa (10,800 psi)	36.5 MPa (5300 psi)
Abrasion Resistance:	Not Measured	4.5%
Chloride Permeability:	1010 Coulombs	2800 Coulombs
Entrained Air:	0%	5.7%
Freeze-Thaw Durability:	100%	N/A

Instrumentation Five of the girders in the bridge were instrumented (three of the girders in the 42-m- (137-ft-) long span and two in a 24-m- (80-ft-) long span). The instrumentation allowed evaluation of internal concrete temperature during curing, end slip of the strands at detensioning, concrete strains, prestress losses, camber, and deflection.

Construction The construction contract was awarded in July 1996. The I-girders for the bridge were fabricated by Central Pre-Mix Prestress Co. of Spokane, WA, who also worked with the University of Washington to produce the research girder. Mowat Construction Company was the general contractor, and the ready-mix concrete supplier was Lone Star Northwest of Seattle, WA. The bridge was completed in January 1998. The bid cost per linear foot of the girder was $153 ($502 per linear meter), compared to the engineer's estimate of $115 per linear foot ($377 per linear meter). The higher cost was attributed to instrumentation. Otherwise, the HPC girder costs about $4 more per linear foot ($13 more per linear meter) than similar girders made of conventional concrete.

Benefits Using high-strength HPC concrete in conjunction with the 15.2-mm (0.6-in) strands, the WSDOT designers were able to use two fewer girders per span than if conventional concrete and strands had been used. In addition, the structure's life will be enhanced because of the durability benefits associated with HPC. ■

U.S. Department of Transportation
Federal Highway Administration

Updated August 2000
FHWA-RD-00-124

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Virginia Avenue Over the Clinch River, Richlands

General Description The initial Virginia Department of Transportation (VDOT) HPC program consisted of seven bridges to be built with HPC in the 1995-1997 construction seasons. The Richlands bridge was one of them and it consists of two 22.6-m (74-ft) spans with five American Association of State Highway and Transportation Officials (AASHTO) Type III prestressed concrete I-beams per span. The project was conducted by VDOT in cooperation with the Virginia Transportation Research Council.

Outline of HPC Features The HPC components had both compressive strength requirements and chloride permeability requirements based on the particular member's use in the structure. The requirements for all elements measured at 28 days were:

Element	Compressive Strength, MPa (psi)	Chloride Permeability, coulombs
Beam@Transfer	46 (6600)	
Beams	69 (10,000)	1500
Deck	34 (5000)	2500
Substructure	21 (3000)	3500

Pretensioned Beams Two AASHTO Type II prestressed concrete I-beams were fabricated to conduct research on the bond of 15.2-mm- (0.6-in-) diameter pretensioned strands and to develop concrete mixes and fabrication procedures. The beams, pretensioned with 15.2-mm- (0.6-in-) diameter strands at 51-mm (2-in) spacing, were used to determine the transfer and development lengths of the strands and were tested to failure. All beams failed in flexure at measured loads that exceeded the calculated ultimate load. Pull-out tests were also made on untensioned 15.2-mm- (0.6-in-) diameter strands embedded in a concrete block. The beams for the actual bridge were AASHTO Type III prestressed concrete I-beams, containing 15.2-mm- (0.6-in-) diameter strands at 51-mm (2-in) center-to-center spacing. The concrete mix for the beams is shown below:

I-Beam Mix	per m^3	per yd^3
Type I Cement	446 kg	752 lb
Silica Fume	45 kg	75 lb
Crushed Limestone (No. 7 Coarse Aggregate)	992 kg	1671 lb
Fine Aggregate	801 kg	1350 lb
Water	139 kg	235 lb
High-Range Water Reducer	7975 mL	207 fl oz
Air-Entraining Agent	255 mL	6.6 fl oz
Retarder	957-1148 mL	25-30 fl oz

HIGH-PERFORMANCE CONCRETE

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Substructure The substructure was built using normal concrete with the addition of the permeability requirement.

Deck The deck contained low-permeability concrete with a compressive strength that was 25 percent higher than that used in conventional concrete decks.

Deck Mix	per m^3	per yd^3
Type I Cement	332 kg	560 lb
Fly Ash	83 kg	140 lb
Crushed Limestone (No. 7 Coarse Aggregate)	1023 kg	1724 lb
Fine Aggregate	596 kg	1004 lb
Water	187 kg	315 lb
Air-Entraining Agent	189 mL	4.9 fl oz
Retarder	810 mL	21 fl oz

Concrete Evaluation The following properties were measured for the concrete in the beam and the deck:

- Slump
- Air Content
- Air-Void Spacing Factor (deck only)
- Concrete Temperature
- Compressive Strength at 28, 56, and 365 days (and at 1 day for the beams and at 7 days for the deck)
- Modulus of Elasticity
- Splitting Tensile Strength
- Freeze-Thaw Durability
- Chloride Permeability

Construction The contract was let in late 1996 and the bridge was opened to traffic in December 1997. The general contractor was Patrick Construction Co., Inc.; the precast/prestressed concrete fabricator was Ross Prestressed Concrete, Inc.; and the ready-mixed concrete supplier was McClure Concrete Co., Inc.

Benefits The original design called for seven AASHTO Type III prestressed concrete beams per span, using conventional concrete, and conventional prestressing strands. Because of the research program done as part of this bridge project, VDOT was able to change the design and produce a more economical structure. VDOT's new bridge design used the HPC mix, five beams instead of seven, and the larger diameter [15.2 mm (0.6 in)] prestressing strands at a 51-mm (2-in) spacing. The unit cost (total cost of the bridge divided by the area of the deck) of \$657/m^2 (\$60/ft^2) was lower than the average cost of \$743/m^2 (\$69/ft^2) for similar bridges let at that time by VDOT. ■

U.S. Department of Transportation
Federal Highway Administration

Updated August 2000
FHWA-RD-00-123

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U.S. 401 Over the Neuse River, Raleigh

General Description This HPC bridge consists of two parallel structures, each with four spans—two spans of 28.0 m (91.9 ft) and two spans of 17.5 m (57.4 ft). Each bridge is 14.4 m (47.1 ft) wide and carries a 12.0-m (39.4-ft) roadway section and a 1.9-m (6.2-ft) sidewalk. The bridges used simple-span prestressed concrete I-girders made continuous for live load. American Association of State Highway and Transportation Officials (AASHTO) Type IV prestressed concrete I-girders were used in the 28.0-m (91.9-ft) spans, while AASHTO Type III prestressed concrete I-girders were used in the 17.5-m (57.4-ft) spans. Girder spacings were five girders per span at 3.12 m (10.25 ft) on center and the deck thickness was 215 mm (8.5 in).

Outline of HPC Features HPC was used in the girders and in the deck. The HPC has the following strength requirements:

Element	Compressive Strength
Girder@Transfer	48 MPa (7000 psi)
Girder@28 days	69 MPa (10,000 psi)
Deck@28 days	41 MPa (6000 psi)

In addition to the strength requirements, the HPC mix was formulated to provide resistance to chloride ion intrusion, freeze-thaw durability, and resistance to internal chemical attack.

HIGH-PERFORMANCE CONCRETE

Concrete with enhanced durability and strength characteristics. Under the Strategic Highway Research Program (SHRP), more than 40 concrete and structural products were developed. To implement the new technology of using High-Performance Concrete (HPC), the Federal Highway Administration (FHWA) has a program underway to showcase bridges constructed with HPC. The objective is to advance the use of HPC to achieve economy of construction and long-term performance.

Pretensioned Girders The AASHTO Type IV prestressed concrete I-girders are 1372 mm (54 in) deep, while the AASHTO Type III prestressed concrete I-girders are 1143 mm (45 in) deep. All of the girders are pretensioned with 15.2-mm- (0.6-in-) diameter straight and draped strands. They are all simple-span girders made continuous for live load. The concrete mix proportion for the HPC girders is shown below:

Girder Mix	Per m^3	Per yd^3
Cement (Type I)	534 kg	900 lb
Silica Fume	30 kg	50 lb
Fine Aggregate	537 kg	905 lb
Coarse Aggregate	1187 kg	1961 lb
Water	164 L	43 gal
Retarder	1393 mL	47.1 fl oz
Air Entraining Agent*	66 mL	2.2 fl oz
High-Range Water Reducer (Superplasticizer)	3133 mL	106.0 fl oz

**The air entraining agent is varied to maintain 3 percent to 6 percent air content.*

Deck The 215-mm (8.5-in) normal-weight concrete deck is formed with metal stay-in-place forms and is subject to a mandatory 7-day wet cure. The 28-day strength of the concrete is 41.3 MPa

(6000 psi) and includes 20-percent substitution of Class F fly ash for portland cement.

Concrete Tests The following properties are being measured by North Carolina State University researchers for both the girder and deck concretes:

- Compressive Strength
- Modulus of Elasticity
- Chloride Permeability (deck only)
- Shrinkage
- Creep
- Internal Concrete Temperature (heat of hydration)
- Coefficient of Thermal Expansion

Instrumentation Internal and external instrumentation are being installed on four girders. The temperature will be monitored during girder curing and during the structure's life at critical locations on the girders. Structural behaviors, such as camber deflection, prestress losses, and continuity reinforcement stresses, are also being monitored/evaluated. Measurements are also taken to determine strand transfer length. Monitoring was initiated at the fabrication plant and will continue for a period of 3 years after the structures are completed.

Construction The bridges were let to contract in November 1998. The general contractor for the bridges is W.C. English, Inc. of Lynchburg, VA. The prestressed concrete girder fabricator is Carolina Prestress, L.L.C. of Charlotte, NC, while the ready-mix concrete supplier is Southern Concrete Materials of Charlotte, NC. Fabrication of the girders began in Spring 1999 and the deck of the first structure was cast in Fall 1999. The first structure was completed in Spring 2000, but is not yet open to traffic. Construction for the second of the two bridges has not yet begun.

Benefits A reduction in the number of girders, diaphragms, and bearings offset the additional cost of the high-performance concrete. The life-cycle cost-savings are expected to be significant due to enhanced durability. Instrumentation of the girders will provide valuable insight into future use of 15.2-mm- (0.6-in-) diameter strands, fly ash in bridge decks, and mix design requirements for 69-MPa (10,000-psi) concrete. ■

U.S. Department of Transportation
Federal Highway Administration

Updated August 2000
FHWA-RD-00-125

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